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Applicability of Agent-based Model to Managing Roadway Infrastructure

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APPLICABILITY OF AGENT-BASED MODEL TO MANAGING ROADWAY INFRASTRUCTURE

by

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Dedication

To My family and friends

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My family has always supported me greatly. Without them, I could not have moved halfway across the Earth for graduate school. I thank them for their unwavering love and support. Thank you, Mom. Your optimism and encouragement have made me who I am, and to you I dedicate this thesis.

Abstract

Applicability of Agent-based Model to Managing Roadway Infrastructure

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In a roadway network, infrastructure conditions determine efficient network operation and traveler safety, and thus roadway engineers need a sophisticated plan to monitor and maintain network performance. Developing a comprehensive maintenance and rehabilitation (M&R) strategy for an infrastructure system, specifically a roadway network, is a complicated process because of the system uncertainties and multiple parties involved. Traditional approaches are mostly top-down, and restrict the decision-making process. In contrast, agent-based models, a bottom-up approach, could well simulate and analyze the autonomy of each party and their interactions in the infrastructure network. In this thesis, an agent-based model prototype was developed to simulate the operations of a small roadway network with a high degree of simplification. The objective of this study is to assess the applicability of agent-based modeling for infrastructure management problems through the following four aspects: (1) to simulate the user route selection process in the network; (2) to analyze the impact of users' choices

on the congestion levels and structural conditions of roadway sections; (3) to help the engineer to determine M&R strategies under a certain budget; and (4) to investigate the impact due to different fare rates of the toll road section on the infrastructure conditions in the network. This prototype detected traffic flow, and gave appropriate M&R advice to each roadway segment. To improve this model, more investigation should be conducted to increase the level of sophistication for the interaction rules between agents, the route selection, and the budget allocation algorithm. Upon completion, this model can be applied to existing road networks to assist roadway engineers in managing the network with an efficient M&R plan and toll rate.

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Chapter 1: Introduction

1.1 Background and Research Problem

In most metropolitan areas, the population grows and the city expands. The number of daily commuter trips increases dramatically due to increasing numbers of local residents. Sometimes, transportation services and infrastructures can barely meet the increasing demand. Thus, many problems emerge in transportation systems, such as roadway congestion, and facility decay. These problems have an adverse impact on the residents' daily lives.

In some urban transportation systems, two categories of roadway sections comprise a road network: public roadways, and toll roads. The overall performance of the network is evaluated based on not only the performance of each roadway section, but also the overall performance of the network as a whole (Robert & Poole, 1992). The condition of a road section can be assessed by two criteria: physical conditions and functional conditions. Physical conditions of roadway segments are usually assessed by the pavement structural conditions, and functional conditions can be evaluated by service-related indices such as congestion severity (Minderhoud, Botma, & Bovy, 1997). In a road network, different users may choose different routes to travel between the same origin and destination, based on their previous experience, preference, and also their perceptions of current road conditions. If a road segment offers satisfactory service, it will attract more road users, which in turn increases the deterioration speed of the physical infrastructures, and the congestion severity of this road segment. To meet the increasing demand, transportation engineers need to work on improving the conditions of road segments.

1.2 CURRENT SITUATION AND RESEARCH MOTIVATIONS

Transportation services and infrastructures have become more and more complex, interacting with social, financial, economic, political, and engineering issues. The effectiveness of the traditional top-down approach to analysis has been questioned for such complex systems in which active interactions and communications exist among individuals and their surrounding environment. To address these problems, researchers are switching their focus to new bottom-up approaches (Adler, Satapathy, Manikonda, Bowles, & Blue, 2005), where system performance and behavior are evaluated by aggregating individual behaviors. Among the various new approaches to model the transportation and infrastructure system, the agent-based modeling approach has unique characteristics, and has been applied to various fields including o solve transportation engineering problems (Kikuchi, Rhee, & Teodorovic, 2002). By bringing together individual agents, this approach provides a high degree of freedom for the agents to interact with each other, and the surrounding environment.

In this thesis, an agent-based model was developed to to assess the applicability of agent-based modeling for infrastructure management proglems by investigating the impact of user route choices on roadway infrastructures. Different road users travel through different routes to their destinations, and such choices lead to various degrees of structure deterioration. Four types of agents were identified in this project: users, engineers, public roadways, and toll roads. As an initial prototype, a small road network consisting of 22 public road sections and two toll road sections was modeled, and to simplify the problem, all road users have determined destinations before they depart. The model recorded the traffic flow and pavement structural conditions of each roadway section. The simulation of this scenario was run for 20 years. In addition, this model generated M&R strategies for traffic engineers to better maintain the roadway pavements. Based on this model, the network can be expanded and other details can be added. With further refinement, this modeling framework may be used to simulate a complete existing road network.

1.3 ORGANIZTION OF THE THESIS

In this thesis, the first chapter briefly introduces the background of the research problem, the motivation to investigate and solve this problem, and the general descriptions of the model prototype developed. In Chapter 2, a literature review regarding the concepts involved in this thesis is presented, including the roadway physical condition assessment, the functional condition assessment, the pavement management systems and resource allocation concept, and the toll road operations. Chapter 3 introduces key concepts related to agent-based modeling, covering from the fundamental definietions of agents, agent-based modeling complexities, the typical agent-based model structure, to the advantages and limitations of the agent-based modeling approach. Then, the detailed problem description and solution methodology are discussed in the Chapter 4, where agent definitions, model framework, and a numerical case study are presented. Chapter 5 illustrates the model output and a brief discussion of the case study. Finally, Chapter 6 summarizes the work conducted under this tudy, presents the conclusions, and provides recommendations on potential future work that can be performed to improve this model.

Chapter 2: Literature Review

2.1 The Physical Condition Assessment of a Roadway Section

The structural conditions of a road network are primarily represented by the pavement conditions of each roadway section. In general, four characteristics of pavement conditions are used in evaluating pavement rehabilitation needs: pavement roughness (rideability), pavement distress (surface conditions), pavement deflection (structure adequacy), and skid resistance (safety). Pavement roughness, the irregularities or roughness of the pavement surface, affects the comfortability of passengers' rides. In this project, pavement roughness is used as the major assessment factor for the pavement conditions of a roadway section (Garber & Hoel, 2009). Two terms are defined by AASHTO to test the serviceability of a roadway, present serviceability rating (PSR), and present serviceability index (PSI). The PSR of a pavement section is given according to how the roadway serves its intended traffic, and this rating is based on the observation and judgment of individual assessors. PSR is a relatively subjective descriptor of the pavement roughness. In contrast to PSR, PSI describes the pavement conditions based on physical measurement. PSI is a relatively objective means of estimating the pavement roughness. The pavement serviceability-performance concept was developed during the AASHO Road Test (Carey & Irick, 1960). In this thesis, the pavement performance and structural conditions of different roadway sections are compared and ranked by their PSI values.

Traffic is the most significant factor that affects pavement conditions, and both traffic loading magnitude and number of load repetitions should be considered to evaluate the impact on the pavement structures. However, since wheel/axle loads vary from one individual vehicle to another, it is complicated to determine the number and types of the axle loads that a pavement section can take during its design life. Besides, the damage due to the wheel/axle load is the primary concern when predicting the pavement performance, instead of the specific wheel/axle load itself. Therefore, it is a common approach to convert mixed traffic loads with different magnitudes and repetitions to an equivalent number of standard loads. The equivalent single axle load (ESAL) is introduced as such a converter, and it is developed from the data collected at the AASHO Road Test (Huang, 2003). The most commonly used standard reference axle load is an 18,000 lb. single axle with dual tires. The calculated ESALs also depend on the pavement type, flexible or rigid, and the pavement structure. The damage caused by a particular load is roughly related to the load raised to a power of four, though more accurate load equivalent factors (LEFs) based on the AASHO Road Test data are available for use as needed. Equation 1 is used to determine cumulated design ESALs that a pavement section can take.

$$\sum ESALs = T_f TGDL(365)Y \qquad \text{Equation 1}$$

T_f: Truck factor, determined based on the percentage of total repetitions for the load group, equivalent axle load factor for the load group, and average number of axles per truck

T: Percentage of trucks in average daily traffic (ADT)

G: Growth factor

D: Directional distribution factor

L: Lane distribution factor

Y: Design period in years

2.2 THE FUNCTIONAL CONDITIONS OF A ROADWAY SECTION

Congestion severity indicates the functional and operational performance of a road network. Due to the rapid development and expansion of urban cities, traffic congestion on roadway networks has become a severe concern to both road users and operators. The growing congestion is basically due to the increase in traffic demand and the shortfall in roadway capacity, and gives rise to additional delays, extra fuel consumption, and increased road user cost. The growing concern about traffic congestion has led to efforts in evaluating the severity of this problem in a quantitative manner and developing mitigation methods to relieve congestions. A common measure of effectiveness used to describe traffic flow is defined as the level of service (LOS) that characterizes both operational conditions within a traffic stream and highway users' perceptions (Garber & Hoel, 2009).

Level of service expresses the highway's performance at traffic volumes less than capacity, by categorizing traffic flow with corresponding safe driving conditions. LOS designations range from the highest, A, to the lowest, F (Garber & Hoel, 2009). At LOS A, the highway is under free-flow operation, which means motorists are able to travel at their desired speed and have complete mobility in changing between lanes. When the highway operates at LOS B, it is under reasonable free-flow operations, where vehicles can maintain desired speeds but maneuverability within the traffic stream is slightly restricted. LOS C describes the highway operating at or near free-flow conditions, however, there are noticeable increases in the formation of platoons and increases in platoon size on the highway. At LOS D, the traffic flow on the highway is at decreasing free-flow levels. Flow is unstable and passing maneuvers are difficult. LOS E describes operation at capacity, when passing has become virtually impossible, and platoons form longer and more frequently. Last, at LOS F, traffic is congested with demand exceeding capacity, and travel speeds are variable.

2.3 Pavement Management Systems and The Resource Allocation Concept

A pavement management system (PMS) is a set of tools used to assist decision-makers at all levels in making better and more informed decisions (American Association of State Highway and Transportation Officials, 2001). In general, a PMS consists of mutually interacting components as planning, programming, design, construction, maintenance and rehabilitation (Haas, Hudson, & Zaniewski, 1994). The decisions that PMS makes may be affected by some exogenous factors, such as budgets, information, and administrative policies. Currently, PMS is the primary tool to support pavement maintenance and rehabilitation (M&R) activities. Pavement maintenance activities include filling cracks, patching potholes, and other applicable techniques, and such activities are routine, preventive, or reactive (Wang, Zhang, & Machemehl, 2003). Most pavement management process can be categorized as two working levels, network level, and project level. The primary purpose of network-level management is to develop a priority program and schedule of work within budget constraints. At project level, the pavement management process deals with the appropriate time in the schedule to physically implement the network decisions.

Asset management is a systematic process of maintaining, upgrading, and operating physical assets cost-effectively, and supports strategic decision making in civil infrastructure management. In addition, asset management provides a framework for handling both short- and long-term planning (Asset Management, Advancing the State of the Art Into the 21st Century Through Public-Private Dialogue, 1996). Within given constraints on resources, resource allocation process can help identify some alternative options in transportation infrastructure project selection in order to maximize the net benefit to the whole system (Wey & Wu, 2007). It is essential to consider the interdependent relationship among the different projects due to the complexity of the problem in transportation networks. Several methods have been proposed to help with decision making during the resource allocation process, including single-criteria cost/benefit analysis, multiple criteria scoring models, ranking methods, and subjective committee evaluation methods (Ringuest & Graves, 1989; Weingarther, 1966; Horwitch & Thietart, 1987). However, these methods' capability of handling the complex relations between the projects is doubtful.

2.4 THE TOLL ROAD OPERATIONS

Direct pricing of road-use in roadway networks was noted as being helpful for balancing demand and supply by economists from more than three decades ago (Poole, 1992). The primary purposes of collecting tolls from highway users are to relieve congestion of the roadway network, and to collect funds for the roadway projects. Toll amounts collected from each roadway user usually vary by vehicle types, weights, or numbers of axles. Heavy trucks are often charged more than passenger cars. Despite some overlaps, current existing toll routes can be categorized as four groups: 1) routes in highly congested usually suburban areas; 2) outlying routes in metropolitan areas; 3) developed corridors which are parallel to existing roads; and 4) routes in the least developed areas (Muller & Buono, 2002). Although there were significant political and other public-acceptance barriers to implement the direct road pricing around two decades ago, nowadays toll roads have become the top-listed solution for Departments of Transportations (DOTs) to cope with congestion problems and budget shortages.

Chapter 3: Introduction to Agent-based Modeling

3.1 Agent-based Modeling and Complexity

Agent-based modeling is a modeling concept in which various agents exist and interact in a certain manner within a given environment (Crooks & Heppenstall, 2012). In this multi-agent system, each individual agent exchanges information with other agents, interacts with others, and achieves his own goal in the environment. The agent-based approach models the system and simulates the interacting process by aggregating the behavior of each individual agent, in contrast to traditional modeling approaches in which general rules govern the overall behavior of the system. There are no universal governing rules for all agents, but each agent behaves following a set of rules. These interacting rules can be either unique among the group, or similar to those of other agents. The relationship between agents is specified in a variety of ways: reactive, or goal-directed (Crooks & Heppenstall, 2012). Some agents can only respond to stimuli from others or the environment, and make corresponding moves, while other agents are capable of seeking their own goals and their moves are to achieve those goals.

Complexity theory and complex systems provide the theoretical basis for agent-based models (Manson, Sun, & Bonsal, 2012). Complexity helps modelers to underlie concepts when they start to address specific theoretical questions and work in particular areas. Agent-based models also enhance the understanding of complexity concepts in many disciplines, such as the policy fields, the natural sciences, the social sciences, and the humanities and arts. Initially, Agent-based models were used as the set of ideas, techniques, and tools for implementing computational models of complex adaptive systems. The agent behaviors were modeled with relatively simple rules that may result in complex emergent behaviors (Macal & North, 2010). With the recent development of agent-based modeling software, the capability of handling more complex systems has improved. Besides investigating dynamic processes in a simulation, more general kinds of agent-based models have been designed to conduct optimization (Olariu & Zomaya, 2006) or search (Hill, Carl, & Champagne, 2006).

3.2 Structure of an Agent-based Model

Three elements constitute a typical agent-based model: agents, agent relationships, and agents' environment. To create an agent-based model, these three elements must be precisely identified, modeled, and programmed. Figure 1 illustrates the structure of an agent-based model. To make the model run, computational engines are required to simulate agent behaviors, and agent interactions, such as an agent-based modeling toolkit, and programming language. Agents repeatedly execute their behaviors and interactions when the model runs, and such processes are often modeled in time-stepped, activity-based, or discrete-event simulation structures (Macal & North, 2010).

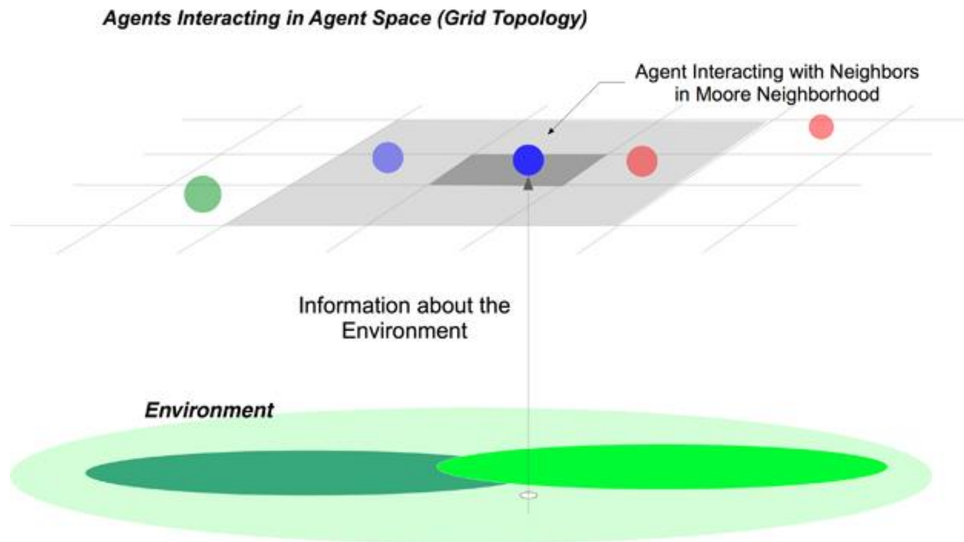

Figure 1 The structure of a sugarscape agent-based model (Epstein & Axtell, 1996)

3.2.1Autonomous Agents

The most important characteristic of agents is their autonomy (Macal & North, 2010). Agents are autonomous entities that are capable of receiving information and communicating with other agents and the environment in order to make their independent decisions (Crooks & Heppenstall, 2012). Agents are active, and have impact on the simulation independently. Some agents are pro-active, and goal-directed. In most cases, they have their own goals, and they act to achieve these goals. Some other agents are reactive and perceptive. They can sense the surrounding environment and be equipped with prior knowledge of the environment. Typically, agents can initiate their actions, rather than simply respond to the system participants and environment.

It is difficult to define what an agent is because there is no universal agreement on this definition (Macal & North, 2010). Based on the literature, an agent is believed to be a self-contained, interactive, and concurrently executing object, an "actor"; an agent is capable of autonomous actions in order to meet its designed objectives; or an agent is a component of software or hardware capable of accomplishing tasks on behalf of its user. Although some ambiguities exist in defining an agent, it is widely agreed that most agents should possess several attributes or abilities, such as autonomy, heterogeneity, social ability, activeness, and learning ability. Every agent can perform actions at each discrete time step, or the actions can be scheduled by the actions of other agents.

3.2.2 Agent Relationships

Primary issues of modeling agent interactions include defining who the agent is, who the agent connects to, and the mechanism of the dynamics of the interactions. Either inanimate or animate agents can possess rules that govern their behaviors and relationships with other agents and the surrounding environment. These rules can be derived from previous literature, expert knowledge, data analysis, or numerical work (Crooks & Heppenstall, 2012). In some agent-based models, agents act based on if-else rules. Specifically, agents will take certain actions when some conditions have been satisfied. Some agents also possess "learning" ability through evolutional computation (Heppenstall, Evans, & Birkin, 2007). Agent relations can be reactive, such as taking actions upon external stimulus; or agents can be goal-directed.

3.2.3 Agent Environments

The space where agents take their actions is defined as the agent environment. The agent environments support the agents' interactions and also can be impacted by the agents' behaviors. Some agents in the environment are spatially explicit, and have geometrical location, regardless of whether these agents are static or not; while some other agents may be spatially implicit, and agents' specific locations are not of importance for their behaviors and interactions with others. In some models, the environment can be modeled as complex environmental models. For instance, atmospheric dispersion models offer location-specific data about atmospheric pollutants that may be accessible by agents. Therefore, agent actions may be constrained by the environment, since the environment may provide limited accessibility and capacity (Macal & North, 2010).

Agent-based models are capable of simulating individual actions of many agents and measuring the overall resulting system behaviors and outcomes over time. This capability makes Agent-based models useful for effects on processes that may operate at different scales and organization levels (Brown, 2006). Some other researchers describe the three constitutions of an agent-based model as sensor, cognition, and actuator (Kikuchi, Rhee, & Teodorovic, 2002). In this scenario, the sensor module perceives other agents and the environment. The cognition module is responsible to control and monitor each individual agent's communications and other behaviors. The actuator module is the actual performer that executes the agent's action plan.

3.3 CHARACTERISTICS OF AGENTS

Besides autonomy, agents often possess certain essential characteristics. Most agents are heterogeneous. An agent could represent a human being that has attributes, such as an age, sex, job, etc. The extent and sophistication of agent heterogeneity determine how much information that will be considered when agents make decisions. In addition, active agents can exert independent influence in a simulation. Various active features can be identified in the agents. As discussed earlier, some agents are goal-directed, and some others are perceptive. Agents can be also bounded rational, which allows them to make inductive, discrete, and adaptive choices that move them toward their goals. It is also assumed that agents are perfectly rational optimizers with unfettered access to information, foresight, and infinite analytical ability (Parker, Manson, Janssen, Hoffmann, & Deadman, 2003). One significant characteristic that allows agents to interact with others is they can communicate extensively. Mobility is another characteristic that most agents have, permitting a wide range of potential uses, although some agents are fixed. Agents can also be adaptive, so they can change their state depending on previous states. This allows agents to adapt to new states with a form of memory or learning. Such adaptions can happen at the individual level, or at the population level.

Agent attributes and agent methods that operate on the agent are associated with an agent in an agent-based model. Some agent attributes are static, not changing with time during the simulation; while some other attributes are dynamic, changeable during the simulation processes. Agent methods can be interpreted as the behaviors that link the agent's situation with its action or set of potential actions. In normative models, agents desire to optimize profits, or utilities. In behavioral models, behavioral theory and empirical data are required to support the application. Figure 2 illustrates a typical agent structure.

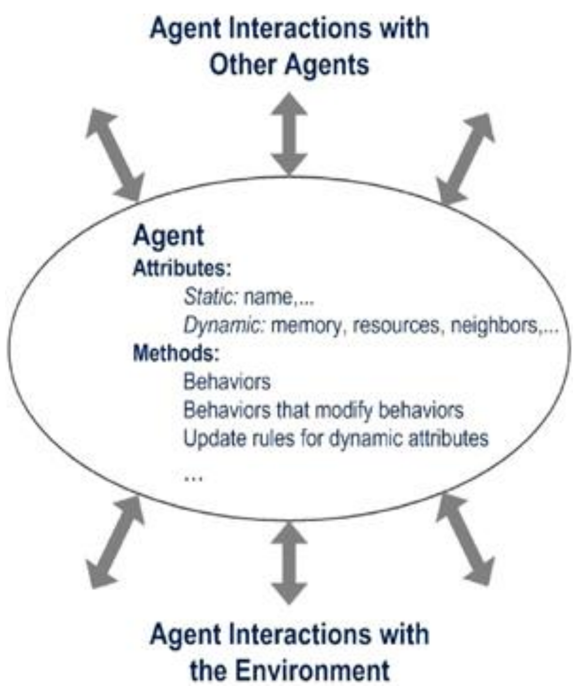

Figure 2 A typical agent (Macal & North, 2010)

3.4 Advantages of Agent-based Modeling

Compared to traditional top-down simulation techniques, an agent-based approach has three main advantages (Crooks & Heppenstall, 2012). First, agent-abased models help capture emergent phenomena. Characteristics of emergent phenomena are difficult to understand and predict with conventional models. However, these phenomena can be revealed by a bottom-up approach describing behaviors and interactions of individual system parts. Second, an agent-based approach provides a natural environment for the study of certain systems, specifically those systems composed of real-world entities. An agent-based approach can be of great use in modeling systems where individual behavior cannot be clearly aggregated; individual behavior is complex; or individual behavior is stochastic. Third, an agent-based approach is flexible, particularly in developing geospatial models. Many agents possess mobility, which benefits spatial simulations. Interactions among agents can be quite complex, but such complexity in turn provides a robust and flexible model framework.

3.5 LIMITATIONS OF AGENT-BASED MODELING

The bottom-up nature of the agent-based approach creates some limitations. First, since no universal rules govern the whole system and individual agents act based on their local state and knowledge, globally optimal decisions within the whole system are difficult to achieve. Besides, constructing an agent-based model requires the modelers to delegate tasks to the agents instead of controlling tasks themselves. This requires that analysts have a high proficiency in modeling skills and a full understanding of how individual agents act. Finally, it is believed that most applications can be solved without the agent-based approach, and sometimes an agent-based model does not give the most appropriate solution (Crooks & Heppenstall, 2012).

Chapter 4: Solution Methodology

4.1 Statement of the Problem

In actuality, within a small road network, users have many route choices to complete their trips. Even if some users share the same origin and destination, they can still choose different routes to arrive at the destination. These different route choices are made based on various factors, such as cost differences, traveler personal preferences, and roadway conditions. Different sections of this road network may serve users with different qualities; some roadway sections in this network can provide users with a higher quality of service, but may require users to pay tolls for their trips. If the user desires to reach his/her destination faster, or get better quality service, he/she may choose to take the toll road. In most cases, the user's first priority in route selection is to minimize the monetary cost, so they stick with public freeways. Such choices result in different monetary and time costs for the user. Each user may value money, time, and other influential factors differently, and incur an individualized combined travel cost for each possible route. The goal of an individual road user is to reach his/her destination with the lowest combined travel cost, or highest utility.

The number of toll road users and the amount of tolls they are willing to pay varies with the availability and serviceability of public freeway sections. If congestion levels increase and the quality of service decreases over the whole freeway network, more users may be willing to pay more for using the toll roads. By adjusting the toll amount, the number of toll road users fluctuates and thus the traffic flow rates and congestion levels of different freeway sections change as well. Each freeway section will have its distinct pavement conditions after several years in service, because of the different number of users traveling through.

The structural conditions of the roadway pavement are highly correlated to the accumulated traffic loading which is a function of the number and the type of users traveling through it. Heavy trucks are much more harmful to the pavement structures than passenger cars. When construction is completed, a new roadway section is assumed to have the best structural conditions and serviceability indices. With an increasing number of trucks, the pavement structural condition deteriorates, and serviceability decreases. When the PSI of a pvenent section drops to a certain value, for example 2.5 on certain roadway classes, the pavement structural condition is generally regarded as being unacceptable, and maintenance work needs to be performed to ensure the serviceability and safety of that road section. The engineer receives a limited amount of public funds to maintain the road network. It is the engieer's responsibility to choose where and how the maintenance work is going to be performed, and to keep the performance level of the whole network at a satisfactory level.

4.2 Definitions of Four Groups of Agents, Agent Attributes Definitions, and Methodological Framework

In this agent-based model prototype, both physical agents, such as the roadway section, and decision-making agents, such as the engineer, are represented. In this model, four types of agents are defined: the toll road, public roadways, the engineer, and users. Each type of the agents has its attributes, actions that it can perform, and interaction rules with others. Table 1 describes each agent type with its associated attributes and actions that have been implemented in this model prototype.

Table 1 Current Agent Definitions

Agent	**Attributes**	**Actions**
The Toll Road	Toll Amount, PSI, LOS, Length	Pavement Deterioration
Public Roadways	PSI, LOS, Length	Pavement Deterioration
The Engineer	Budget Amount, Possible Actions	Detecting the pavement conditions, Determining M&R strategies
Users	Origin and Destination, Route Selection Preference (Value of time, monetary cost, pavement conditions), Vehicle Types (Passenger car/Heavy Truck), ESALs (For Heavy Trucks Only)	Evaluating each possible route, Determining the route, Choosing whether to use the toll road

A comprehensive methodological framework was developed for this agent-based model prototype, to illustrate what factors impact agent decision making, how each agent action affects other agent actions, and how the network performance aggregates from the individual agent participants. The framework is shown as Figure 3, where the flow charts in left-most dashed-line box illustrates the process by which each user agent will make its decision to complete the trip. The three dashed-line boxes in the middle represent both the toll road and public roadway section attributes, how these attributes will be impacted by other agent actions, and also how these values will affect other agent decisions. The top box includes the static attributes that do not vary during the model simulation of each roadway section, while the bottom two boxes contain the dynamic attributes of roadway sections, which will increase or decrease according to other agent behaviors. Behavior rules of the decision maker in this model, the engineer, are shown in the right-most dashed-line box. It illustrates what inputs affect the engineer's decision and how the engineer makes the maintenance and rehabilitation recommendations for the network.

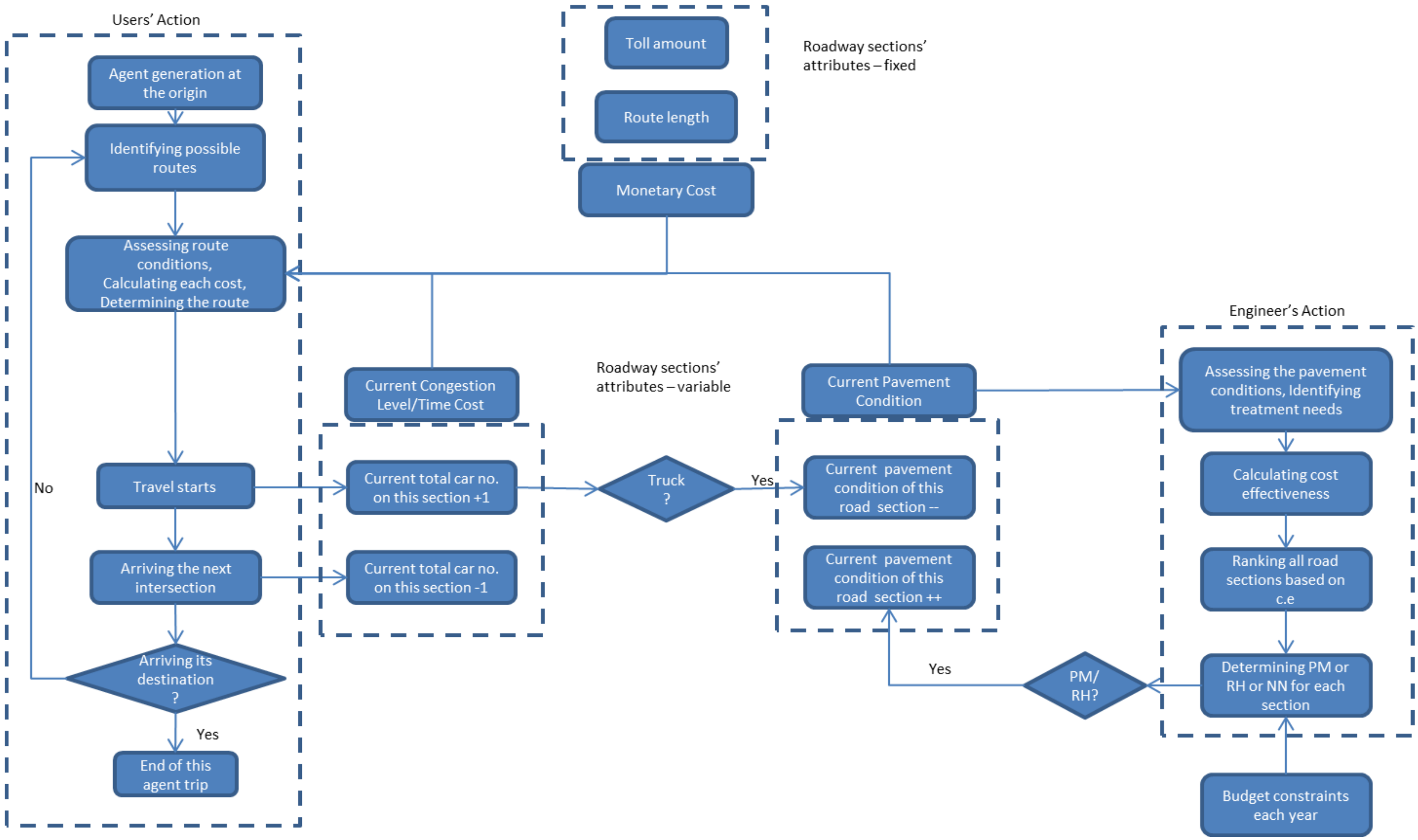

Figure 3 Model Framework

4.3 Descriptions of Agent Relations and Interactions

4.3.1 The Toll Road

The toll road is the most essential agent to define, because the toll amount is a major factor to determine the revenue of a roadway network. The toll road is associated with four main attributes: the toll amount, structural conditions, service levels, and physical location.

The toll amount affects users' route selection significantly. Also, part of the annual total toll collected is used for toll road maintenance work, while the rest is regarded as revenue. Pavement structure serviceability, measured by PSI, indicates the road's present pavement conditions. The structural conditions of a roadway deteriorate because of the cumulative traffic loading of heavy trucks, ignoring passenger cars in terms of their influence on the structural conditions of the roadway pavement. Service levels, measured by LOS, show the serviceability and congestion level of the toll road. The increasing number of vehicles on a toll road indicates the service levels on the public roadways keep decreasing. Physical location is a predetermined attribute of each road section, which includes arcs and nodes. The arc reflects the length of a toll road section; it provides information on travel cost once gasoline cost, toll amount, and travel time with real-time average travel speed (ATS) are known. The node is used to represent an intersection at which users select a route based on their preference.

4.3.2 Public Roadways

Multiple public roadways are alternatives for users to reach their destinations. This type of agent contains three attributes: pavement conditions, service levels, and physical location. These attributes function in the same way as those of the toll road. After public roadways serve for some years, the engineer based on his analyses can perform the maintenance and rehabilitation work on these roadway sections to improve their pavement conditions, with the funding received from public agencies.

4.3.3 The Engineer

The engineer, as indicated previously, is responsible for either maintaining or rehabilitating one or multiple public roadway sections based on the PSI within the budget, given that each year the engineer receives limited funding from public agencies for road improvement work. Preventive maintenance requires less money but can increase PSI by only 0.5. Rehabilitation costs greatly more, but after performed it helps PSI to reset to 4.5.

4.3.4 Users

Users are the most autonomous and complicated agents to define in this model, despite their three attributes, vehicle types, trip origin and destination, and route selection preferences. In terms of vehicle type, only passenger cars and heavy trucks are considered in this case. While both types of vehicles impact the congestion level of the roadway, only heavy trucks exacerbate pavement conditions. Therefore, heavy trucks have another essential attribute, ESALs, that directly contributes to the pavement deterioration. Trucks with heavier axle loads and/or higher values of ESALs will result in more damages to the pavement structures. For each individual user, the origin and destination of each trip is determined before he/she departs, and his/her final destination will not change during the trip. The route selection preference can be complex and vary with each individual. A user selects a route mainly based on time, money, and road conditions. In this prototype modeling, travel time was influenced and calculated by road distance and congestion level. Monetary cost of each tirp was the sum of tolls and gasoline costs. The total travel cost could be determined by the toll rate (dollar per mile) and gasoline cost per unit distance (dollar per mile) multipled by the total distance travled. It is assumed that some user choices may be affected by pavement conditions of the roadway section, though in general, pavement conditions have little impact on most users' route choices. On the other hand, user choices will have a significant impact on congestion levels and pavement conditions of each roadway section.

The attributes of each agent and their interactions are illustrated in Figure 4.

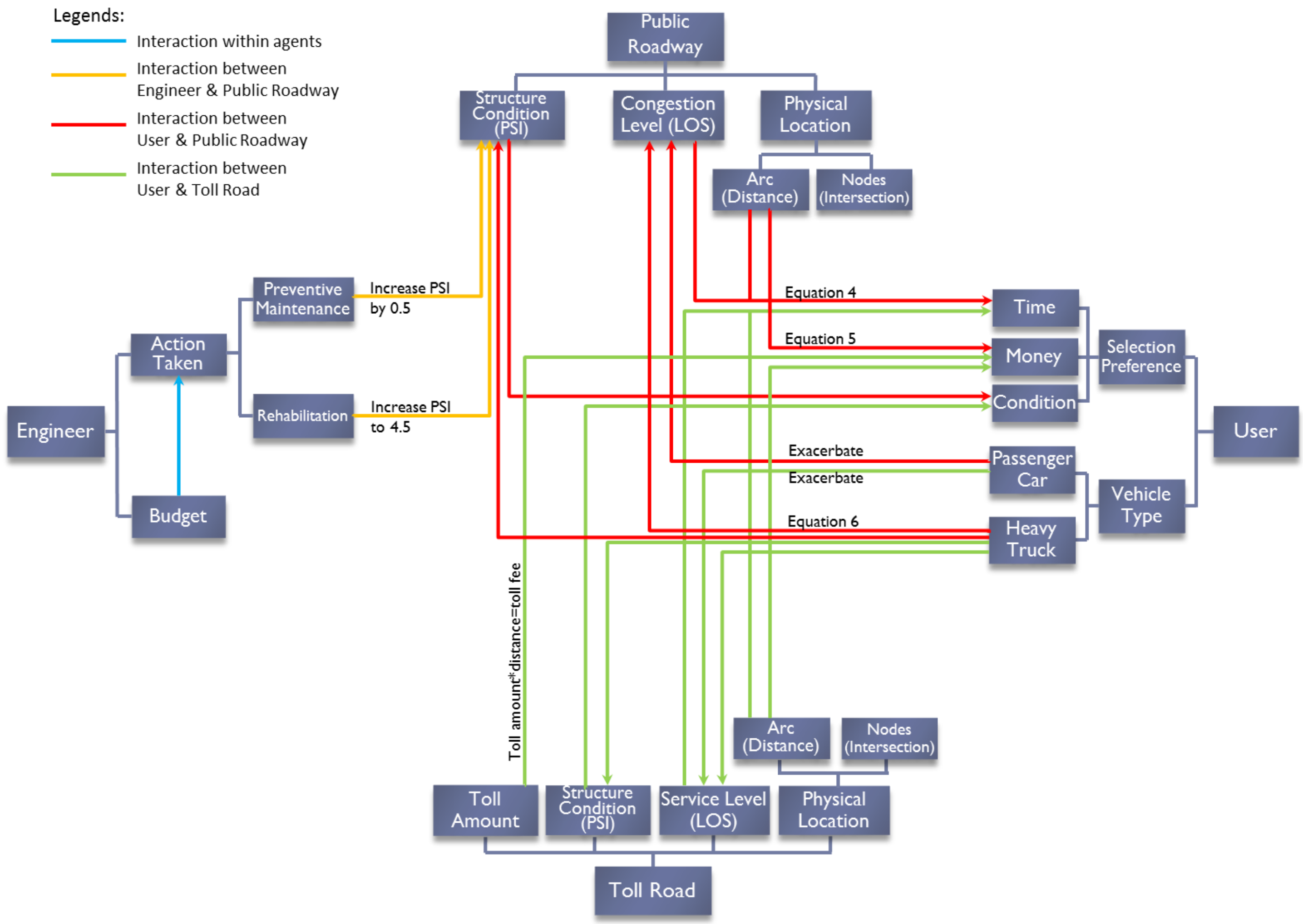

Figure 4 Interactions between Agents

4.4 Model Development – A Numerical Case Study

4.4.1 Model Network

In the numerical case, four types of agents with different attributes were defined as discussed previously. A small road network composed of 12 links and 9 nodes was assumed as shown in Figure 5. In this figure, each node can be the trip origin or destination for an individual user agent. Each user agent will start his/her trip at the origin, and his/her goal is to arrive at his/her destination through the lowest cost route. As inidcated in the figure, each link is assumed to be able to accommodate bidirectional traffic. R_i is the road section (arc) and I_j represents the intersection (node), within which R6 and R18 are the toll road sections and others are public roadways. To simplify the model, an assumption was made that users could not make U-turn or detour based on their selection preference to prevent users from driving circular routes.

At the beginning of the simulation, PSI of each roadway section was set at 4.5, indicating that all roadway pavements provided the best serviceability. By randomly assigning a number of user agents to each roadway section, the simulation of interactions between agents starts; the model performs the simulation for an analysis period of 20 years. The ultimate roadway pavement conditions, ultimate PSI values, are obtained at the end of each simulation year. The optimal M&R strategy is determined based on the budget limitation. The model was developed using the Recursive Porous Agent Simulation Toolkit (REPAST) which is a free open source toolkit developed for agent-based model simulations. In addition, REPAST is object-oriented and can be implemented in Java, which is used in developing this model prototype.

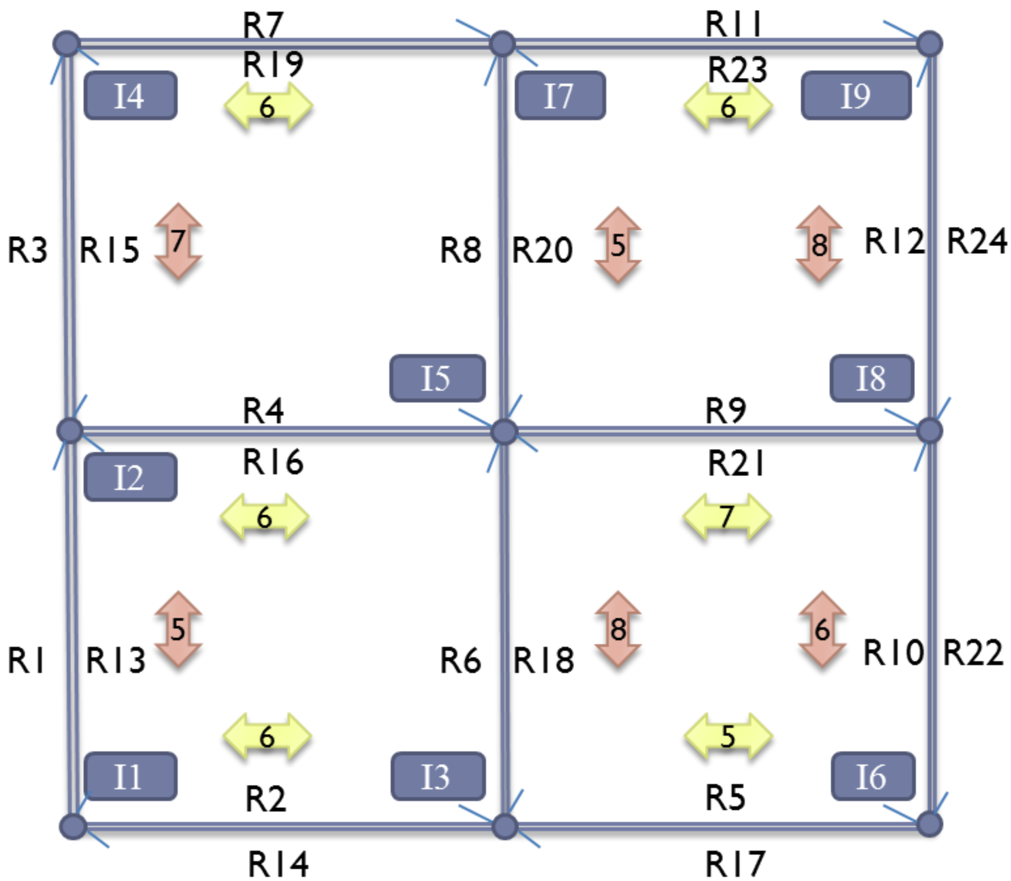

Figure 5 Model Network

4.4.2 Predetermined OD Matrix

As discussed earlier, in this model, each user agent starts the trip from his/her origin, and he/she chooses his/her route to reach his/her desired destination, which is determined before his/her departure. During the trip, although user agents could change routes based on the traffic conditions at that moment, the destination did not change. In this small roadway network, there are nine nodes, which serve as both intersections, and origin/destinations for the user agents. User agents can be generated from these nodes, make their route choices, and complete their trips when they arrive at the desired destination nodes. The number of agents generated from each node destined for another node in the first simulation year is summarized as an origin-destination matrix shown in Table 2.

Table 2 Origin-Destination Matrix (per 10,000 users)

1	Destination									
Origin	1	2	3	4	5	6	7	8	9	Sum
1	0	0	0	0	0	0	0	0	600	600
2	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	450	0	0	0	450
5	150	0	0	200	0	200	0	0	150	700
6	0	0	0	550	0	0	0	0	0	550
7	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0
9	500	0	0	0	0	0	0	0	0	500
Sum	650	0	0	750	0	650	0	0	750	2800

In Table 2, one represents 10,000 users in this table. For example, there were 6,000,000 user agents generated at intersection 1 traveling to intersection 9 in the first year. In this case, only intersections 1, 4, 5, 6, and 9 served as origins for user agents, and only intersections 1, 4, 6, and 9 as destinations. The total number of agents generated from each origin would increase year by year with an average growth rate 2 percent.

Among all these road users, 15 percent were heavy trucks, and the rest 85 percent were passenger cars.

4.4.3 Assumptions

Several assumptions were made in this model: (1) All road users preferred to travel to their destinations directly, and no detours would be allowed; (2) 15 percent of the total road vehicles were heavy trucks, and 85 percent were passenger cars; and (3) The design life of the pavement structure under LOS C was 20 years, which can be converted to a maximum number of 113.88×10^6 passenger cars traveling through that roadway section.

4.4.4 Route Selection Rules

Users selected routes based on three factors: travel time, monetary cost, and structural conditions. At each intersection, users were informed of these factors based on real-time information. Each user would weight these factors differently according to their individual selection preferences. Therefore, in the simulation, a weight for each factor was randomly assigned to every user. Next, the user would calculate a weighted average score for every possible route and chose the lowest one. In order to achieve agent autonomy, the exact values of the weights were randomly assigned by REPAST.

Table 3 lists the possible routes at each intersection for the user group with origin at I1 and destination at I9. The possible routes for other user groups are similar, so the detailed route combinations are omitted here. Equation 2 shows the calculation of weighted average scores. The weights of travel time and monetary cost vary from 0 to 1 among all user agents. In terms of structural conditions, since a higher PSI stands for better conditions, but the user prefers a lower weighted score, the weight for this attribute is adjusted to -0.05 to 0.

Table 3 Possible Routes from I_1 to I_9 at Each Intersection

Intersection I_j	**Possible Routes**
I_1	R_1—R_3—R_7—R_{11}
	R_1—R_4—R_8—R_{11}
	R_1—R_4—R_9—R_{12}
	R_2—R_6—R_8—R_{11}
	R_2—R_6—R_9—R_{12}
	R_2—R_5—R_{10}—R_{12}
I_2	R_3—R_7—R_{11}
	R_4—R_8—R_{11}
	R_4—R_9—R_{12}
I_3	R_5—R_{10}—R_{12}
	R_6—R_9—R_{12}
	R_6—R_8—R_{12}
I_4	R_7—R_{11}
I_5	R_8—R_{11}
	R_9—R_{12}
I_6	R_{10}—R_{12}
I_7	R_{11}
I_8	R_{12}

$$Score\ (Ri) = \sum_{k=1}^{3} A_k \times C_k \qquad \text{Equation 2}$$

A_k: Normalized value of each factor

C_k: Weight for each attribute

k = 1, travel time; *k* = 2, monetary cost; *k* = 3, structural condition

As the range of values for each factor is different, these values cannot be directly used for weighted average calculation, so it is necessary to normalize the results. Min-max normalization was applied as shown in Equation 3. The results are normalized within a range of 1-10.

$$A' = \frac{A - min_A}{max_A - min_A} \times (new\_max_A - new\_min_A) + new\_min_A \qquad \text{Equation 3}$$

A: Initial value that needs to be normalized

A': Normalized value

max_A/min_A : Maximum/minimum value of the initial data set

new_max_A/new_min_A : Maximum/minimum value of the new data set

4.4.4.1 Travel Time

Travel time is calculated with Equation 4:

$$T_i = D_i/ATS_i \qquad \text{Equation 4}$$

T_i: Travel time of road section *i*

D_i: Distance of road section *i*

ATS_i: Average travel speed (ATS) of road section i

In this equation, D_i is determined by the road sections' physical length. As shown in Figure 6, in the case study, ATS_i is linearly related to Level of Service (LOS). Table 4 below lists the definition of each LOS and the calculation of the corresponding ATS, and shows how each LOS is presented in the simulation results by REPAST. ATS is a real-time parameter that can be affected by the number of passenger cars on the road section. When calculating the number of passenger cars, it is assumed that one heavy truck equals 3.5 passenger cars. At the beginning of the simulation, each road section was randomly assigned a LOS and a certain number of vehicles.

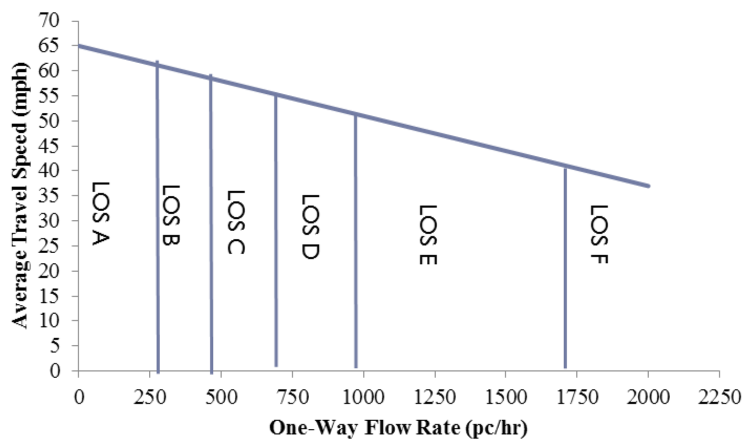

Figure 6 Level of Service vs. Average Travel Speed

Table 4 Relations between LOS and ATS

LOS	Number of Passenger Cars (x)	Average Travel Speed (mph)
A	0-300	ATS=65-0.0147x
B	301-450	
C	451-650	
D	651-1000	
E	1001-1700	
F	1701-3000	

4.4.4.2 Monetary Cost

The monetary cost of each trip is proportional to the length of the route selected. For public freeway sections, the major cost associated with the trip is gasoline consumption. The gasoline cost rate of \$0.15/mile is used in this model, and the total gasoline cost of traveling through a roadway section is equal to the product of the road length and this rate. Gas cost for roadway section *i* is calculated as below:

$$Gas\ Cost_i = L_i * GR \qquad \text{Equation 5}$$

L_i: Length of roadway section i

GR: Gas rate, in this case \$0.15/mile

Besides the gasoline cost, if the user chooses a toll road, he/she pays an additional cost for each mile traveled. In the case study, the toll rate for each road section is adjustable. Determining an optimal rate that complies with the model requirement is one of the objectives. Initially, the toll rate was set to \$0.2/mile, resulting in the total toll amount of \$1.60 for traveling on this section.

4.4.4.3 Structural Conditions

The pavement structural condition of a pavement section deteriorates with the increasing number of heavy trucks traveling through the section. The PSI is affected by the accumulated traffic load, and in this case, the accumulated number of ESALs passing by. The average load equivalent factor (LEF) of a typical heavy truck is assumed to be 1.7, and in this model, LEFs for heavy trucks had a range from 0.6 to 2.8. The exact LEF value for each heavy truck was randomly assigned, with an overall mean LEF value of 1.7. To quantitatively evaluate the pavement structural deterioration, a modified sigmoid performance curve was assumed. In addition, the pavement sections will function satisfactorily under LOS C for 20 years with heavy trucks accounting for 15 percent of total traffic flow. The modified sigmoid performance function is given in Equation 6:

$$P_n = 4.5 - 2e^{1-\left(\frac{15.09*10^6*1.7}{\sum ESALs}\right)^2} \qquad \text{Equation 6}$$

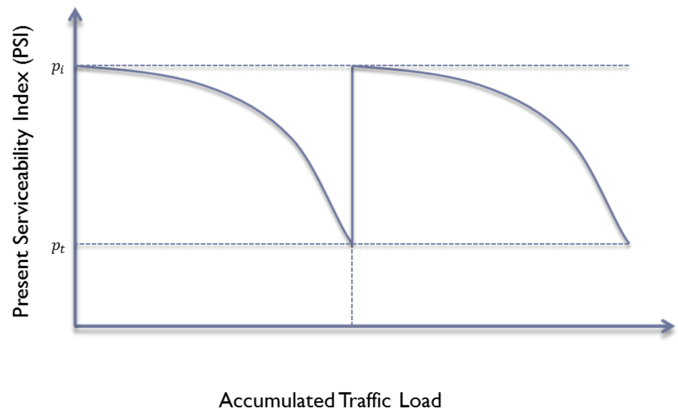

Figure 7 Influence of Accumulated Traffic Load on PSI

P_i: The initial PSI value of the pavement structures, equals 4.5

P_t: The minimum acceptable PSI value of the pavement structures, equals 2.5

At the end of each year, the engineer assesses the structural conditions of all roadway sections, and ranks them according to a specific rule. If the budgets allowed, the engineer decides where and how to perform the maintenance work to improve pavement serviceability. In this case study, it is assumed that two types of maintenance work could be employed to improve the pavement structural conditions: preventive maintenance (PM) and rehabilitation (RH). If the PM is performed, the PSI of that roadway section increases by 0.5; if the engineer decides to rehabilitate that roadway section, the PSI is reset to its maximum value of 4.5.

4.4.5 Budget Allocation Rules

As part of the rules used in this case study, the engineer evaluates the physical performance of each roadway section at the end of each year, and ranks them according to two rules: (1) the worst-first method, and (2) the cost effectiveness analysis. In the worst-first method, the engineer ranks the PSI of a pavement sections from the lowest to highest, meaning that the sections in the worst condition would be repaired first. The second is a cost effectiveness analysis, in which the repair benefiting more users would be performed first. Equation 7 shows how the engineer assesses the cost effectiveness of potential maintenance work, based upon the unit cost for improving pavement PSI and the number of users that would be impacted. Based on such rankings, the engineer makes decisions on where and how the maintenance and rehabilitation work should be performed with limited resources.

$$CE_i = \left(\frac{UC_{ij}}{\Delta PSI}\right)/x_i \qquad \text{Equation 7}$$

CE_i: Cost effectiveness of repairing roadway section i

UC_{ij}: Unit cost of repairing roadway section i with maintenance work j

ΔPSI: The increase of PSI after M&R work

x_i: Current number of user agents on roadway section i

For this case study, it is assumed that each year the engineer receives $1,600,000 for the maintenance and rehabilitation work on this small road network; but although there is no requirement to expend the annual allocation, none could be carried over to the next year. All the repair work is assumed to be conducted after such decisions are made. The unit cost of performing PM to a roadway section was $30,000 per mile per lane, and for the rehabilitation, the unit cost was $120,000 per mile per lane.

Chapter 5: Experiment Results – Model Output

Figure 8 is a snapshot of the simulation process exported from Repast JAVA. The users, represented by blue dots in this figure, are scattered randomly on the roadways with different densities and travel speeds, which change along with the real-time conditions. The actions of users were simulated for a periods of 20 years in the case study. This process allows us to visualize the traffic flow on each road section.

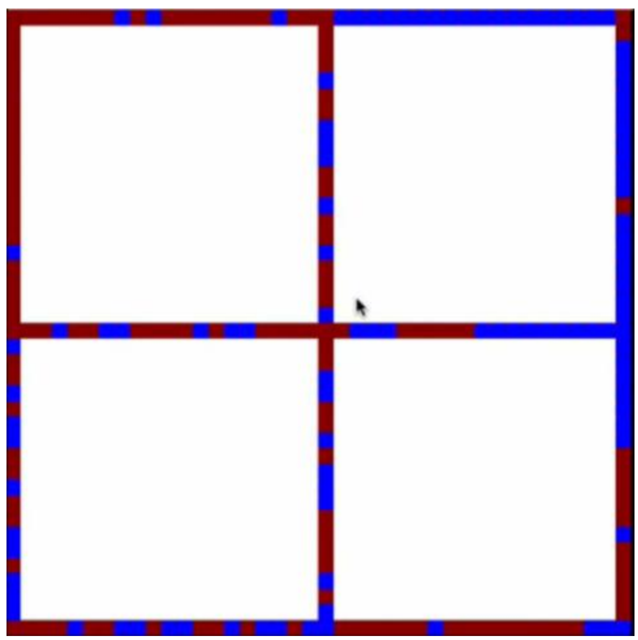

Figure 8 Snapshot of the Simulation Process

5.1 Roadway Section PSI Output of Worst-First Method

An important output of the model is the PSI of each roadway section. First, when the engineer used the worst-first method to determine M&R strategies, the model was run three times with three different toll rates of the toll road section, and the toll rates were set to 10 cents/mile, 20 cents/mile, and 30 cents/mile. The PSIs of roadway sections during the 20 simulation years are shown in Figure 9. The PSIs of two roll road sections, R6 and R18, deteriorated slightly differently under these three toll rates. The overall pavement serviceability is slightly better when the toll rates increase from 10 cents to 30 cents for both R6 and R18. However, though there are only little differences between the PSI values of the toll road sections, the change of toll rates has more impact on the pavement condition deteriorations of other public roadway sections. Roadway sections 2, 11, 13, 14, 18, and 23 attracted more users when the toll rate decreased, whileas fewer users chose to travel through roadway sections 3 and 16 when the toll cost was relatively low.

5.2 Roadway Section PSI Output of Cost-Effectiveness Method

The pavement conditions of each roadway section when the engineer adopted cost effectiveness analysis to determine the M&R strategies are shown in Figure 10. Similar to the worst-first method, the toll rate changes do not affect the pavement conditions on the two toll road sections significantly. However, it is worth noting that for R18 the overall PSI is slightly higher when the toll rate is 20 cents compared to 10 cents and 30 cents, indicating that the toll rate should be neither too low nor too high.

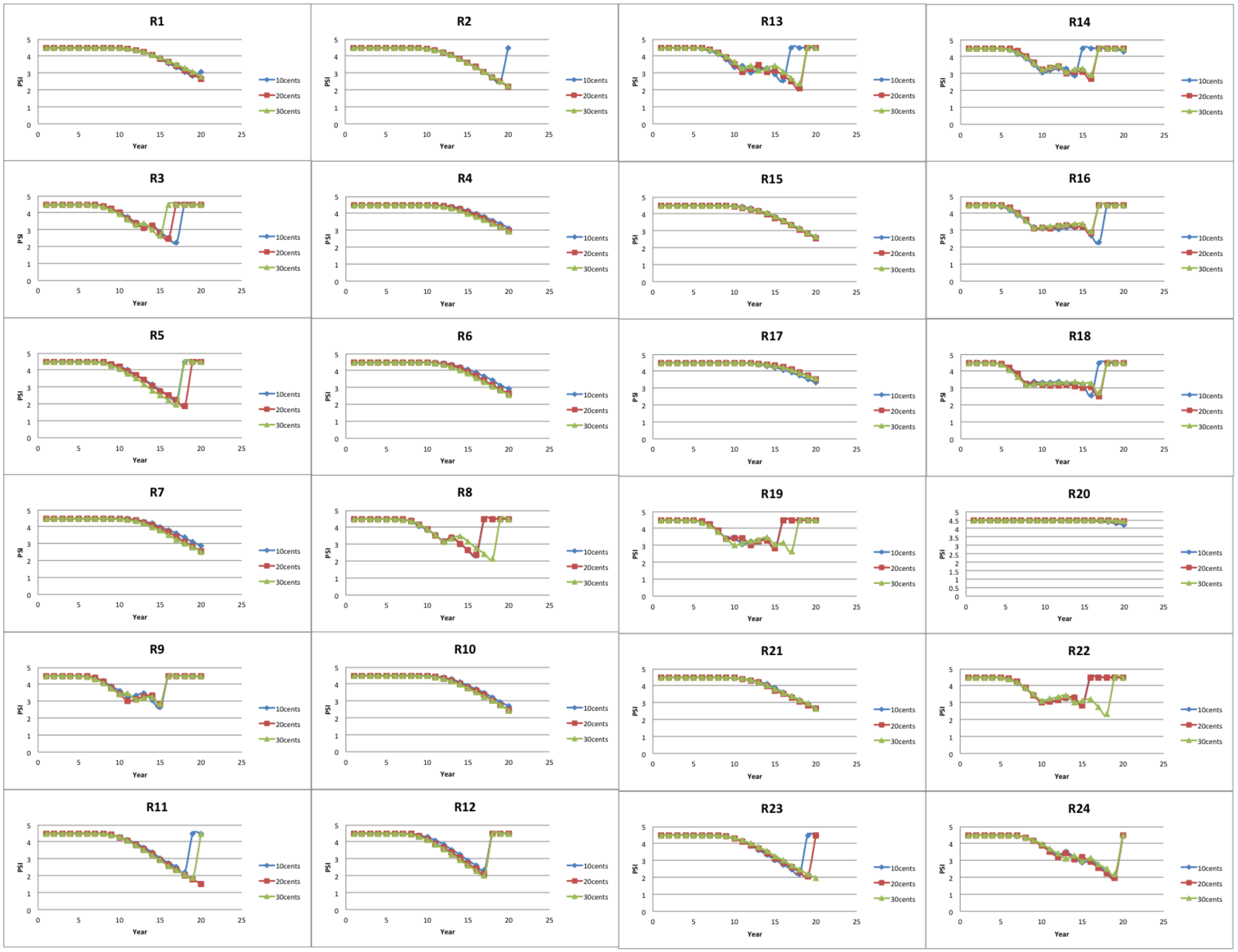

Figure 9 Roadway Section PSIs of Worst-First Method

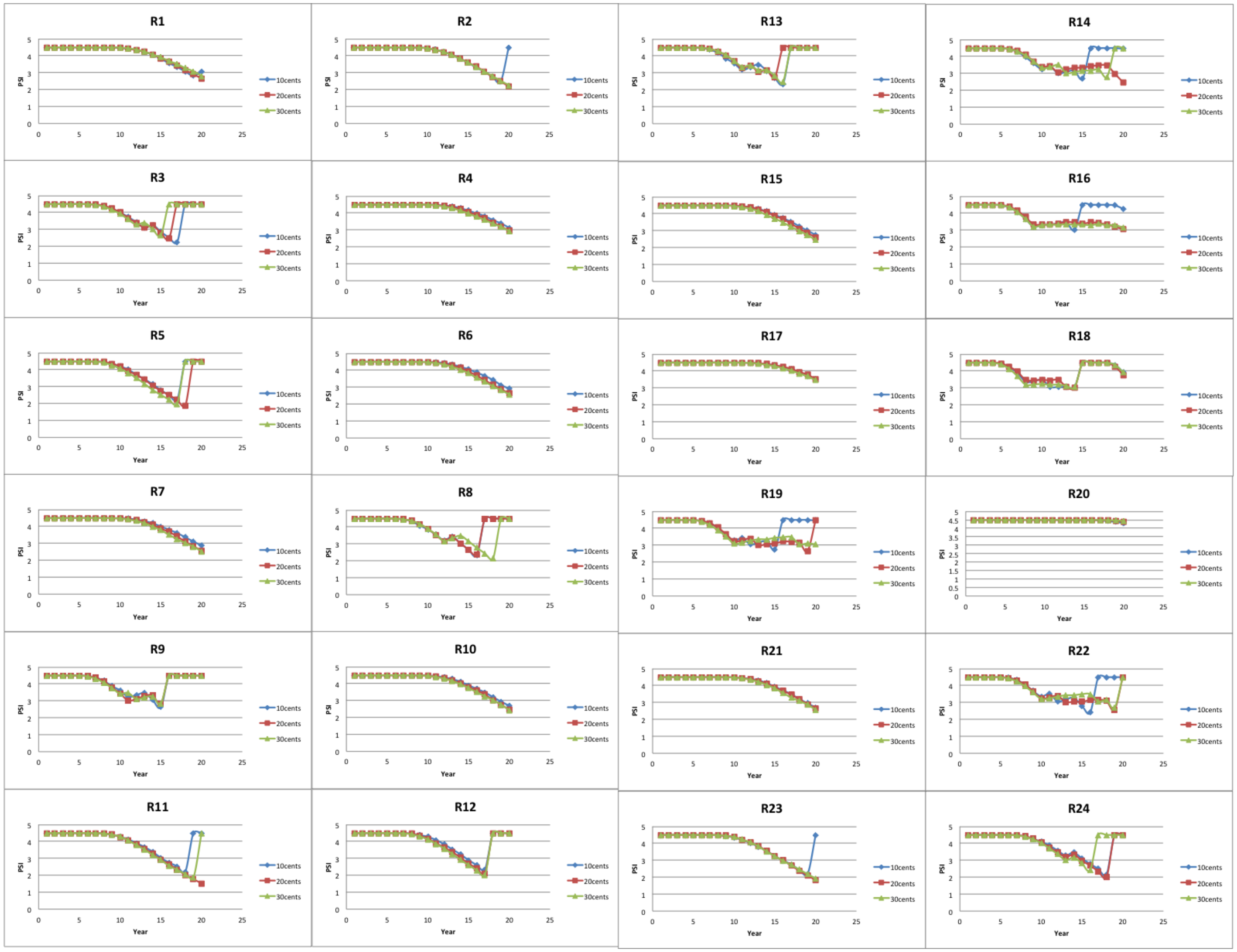

Figure 10 Roadway Section PSIs of Cost Effectiveness Method

5.3 Average System Pavement Conditions

Figure 11 illustrates the comparison of overall system average pavement conditions between the two decision-making methods. The average PSI of this roadway network deteriorated from 4.5 to around 3.5 after the 20 simulation years. The overall decreasing rate of PSI is slightly smaller when the engineer determined M&R strategies based on cost effectiveness analysis. Using cost effectiveness analysis method, after 15 years, the average system PSI value keepsremained at a relatively constant level with the given amount of funding, while when the worst-first method is adopted, the average system PSI drops rapidly during years 13-16, is slightly improved after year 17.

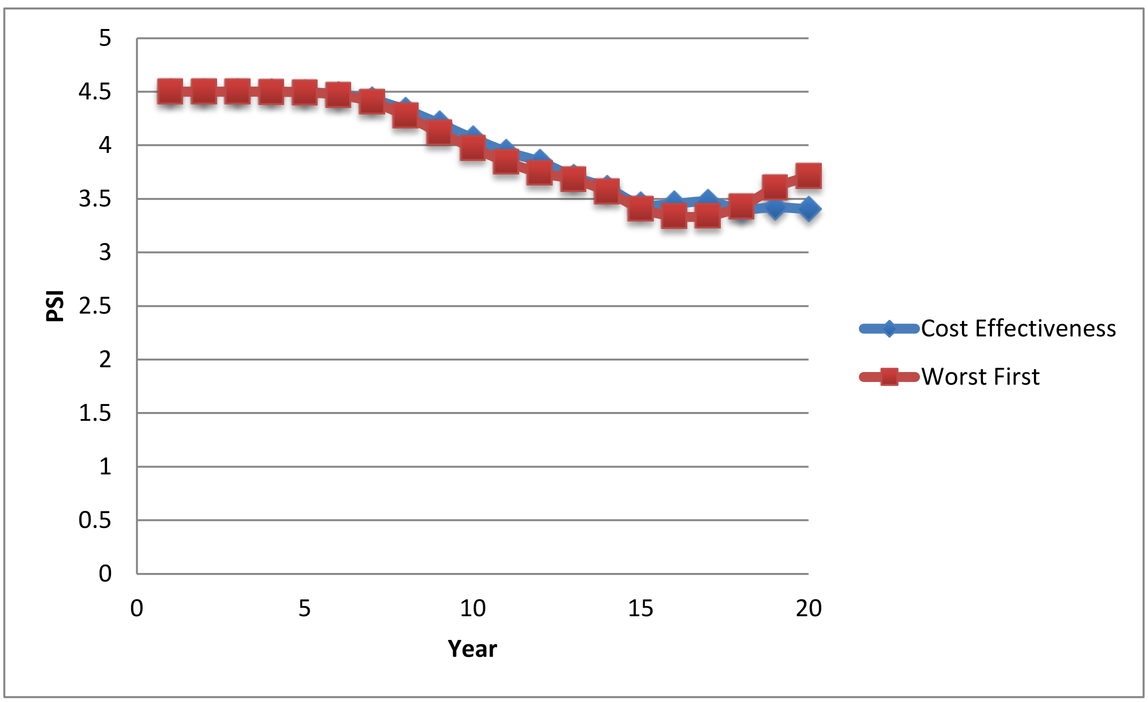

Figure 11 Mean System Pavement Conditions

5.4 CUMULATED M&R COST OF ROADWAY SECTIONS

Figure 12 compares M&R cost on each roadway section between the two selection methods. When using worst-first method as the decision rule, the engineer was inclined to spend more on several roadway sections, such as R18 & R9. More M&R work was performed on these roadway sections to increase their pavement serviceability. It is also observed from Figure 12 that the engineer using cost effectiveness analysis tended to allocate maintenance budget more evenly over the whole network. Also, the less expensive option, PM, was selected more frequently than the more expensive RH. This explains why the mean system-wide PSI value keeps relatively at a steady level after year 15 of the simulation. The given amount of funding was the same for these two decision-making methods, but the actual amount spent each year varied.

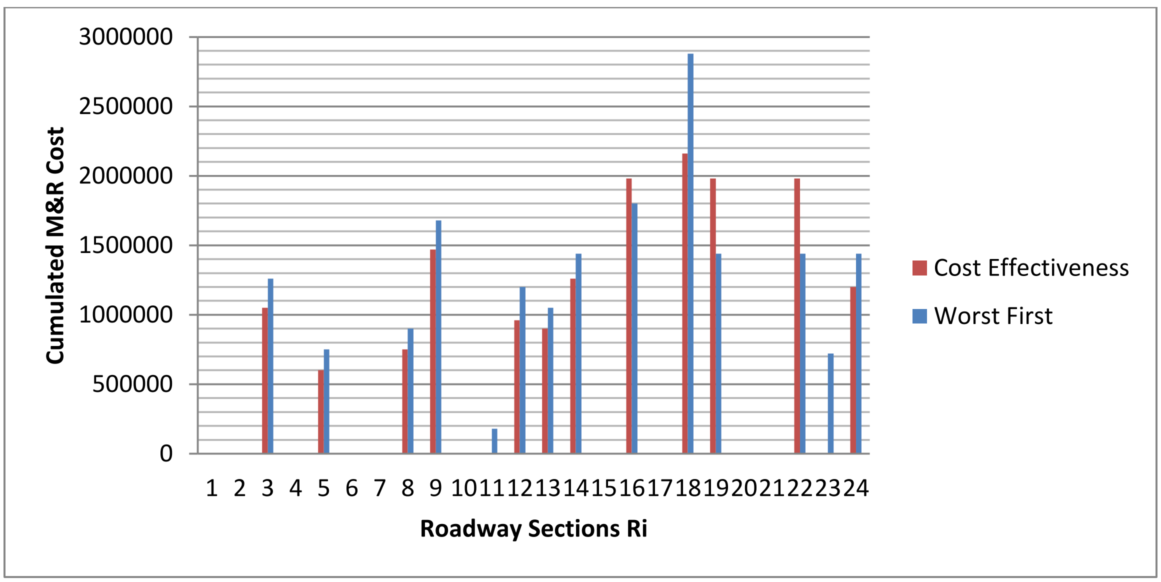

Figure 12 Cumulated M&R Cost for Each Roadway Section

Chapter 6: Conclusions

6.1 Conclusions

Based on the findings from this preliminary exploration of the agent-based modeling approach, the following conclusions are drawn:

1. In this thesis, an applicability study of using an agent-based modeling approach to solving infrastructure management problems was conducted. A prototype model was developed to analyze the impact of the user's route selections on the roadway infrastructure, and to investigate and determine the optimal toll rate and M&R strategies. As indicated by the result of this study, agent-based modeling can be an essential complementation of traditional modeling approaches for researchers to better understand the interdependencies, and catch the emergent behaviors of each participant in transportation infrastructure systems. In this prototype model, reasonable M&R strategies were determined, helping maintain the whole network performance at a satisfactory level. Although certain relationships are difficult to quantify, the basic behavior of the system is well understood, showing that agent-based modeling can be used as an effective tool to gain useful insights about the complex relationships among the roadway congestion, the pavement deterioration, user's route choices, and engineering decisions.

2. An agent-based modeling approach provides an alternative way to formulate and solve infrastructure management problems; it has great advantages over traditional

modeling approaches because of its bottom-up nature. As infrastructure problems become more complex, the behavior of the transportation infrastructure system becomes more and more difficult to predict. The traditional top-down approach has some limitations to analyze such complex interactions within the transportation systems. Therefore, more researchers are using bottom-up modeling approaches, such as agent-based modeling, to handle such complexity. Agent-based modeling focuses on simulating behaviors of individual agents, and the overall system performance emerges from the aggregation of the interactions. Although agent-based modeling succeeds in modeling individual relations and is capable of capturing emergent behavior of individual agents, in some cases, the overall system optimization can hardly be achieved due to the lack of system governing rules. When controlling the outcome of the entire system is not the primary objective, agent-based models possess other advantages compared with top-down modeling approaches, in terms of the ease of model formulation.

3. There are some issues related to the application of agent-based models to the infrastructure management. Agent-based modeling underscores the complexities of managing infrastructure systems and the difficulties in modeling the interactions between agents. The level of detail in simulating individual agents should be carefully considered; otherwise, it can be extremely computation internsive and thus time consuming. In addition, another issue that deserves attention is the difficulties of quantifying, calibrating, and justifying relations between agents, specifically when

human agents involved, since they sometimes behave irrationally and make subjective choices. This may constitute major problems in the outcomes of the model, and therefore the applicability of agent-based modeling to specific problems should be closely examined when qualitative relations dominate among individual participants in the system.

6.2 Recommendations for Future Research

To increase the sophistication and comprehension of the model developed, further work could be done from the following aspects. (1) Improving the model formulations, such as the pavement deterioration model, and the roadway congestion model. (2) Revising the decision algorithms. The engineer's decision making largely depends on the information received, so the engineer's knowledge and information about the whole system could be expanded to make more comprehensive M&R strategies based on the given budgets. (3) Modifying the road network. Road networks could be exported from GIS data to reflect real-world situations and infrastructure systems from which real-time LOS and PSI could be obtained to make the model more realistic. (4) Using real data sets. This model prototype used synthetically generated data; so to improve this model, real-world data set could be implemented, such as the actual number of user agents on each roadway section in the form of AADT counts. (5) Investigating the emergent behavior. This model demonstrated limited emergent behaviors in terms of the gradual deterioration of the pavement condition when it was not funded for maintenance. Other emergencies, such as catastrophic falures of pavement segments, could be modeled to further investigate the responses and interdepencies among infrastructure systems.

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